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# A new approach to the development of zero-emission power generation system

A F Ryzhkov, T F Bogatova, G E Maslennikov and P V Osipov

Ural Federal University, 19 Mira Street, Yekaterinburg, Russia

E-mail: a.f.ryzhkov@urfu.ru

**Abstract.** The problems of tightening harmful emissions standards and meeting commitments to reduce greenhouse gas emissions require the development of environmentally and economically viable technologies to capture CO<sub>2</sub> and its subsequent utilization. The integration characteristics of the generic technologies for CO<sub>2</sub> emission utilization from energy industries with a short, medium- and long-term commercialization prospects are considered, depending on the level of technological maturity and market attractiveness. Potential CO<sub>2</sub> consumers were classified according to the central most sensitive energy generation parameters: volumes, pressure, and purity, depending on the CO<sub>2</sub> capture processes parameters and types of thermal power plants. The CO<sub>2</sub> utilization unit principles designed for full CO<sub>2</sub> capture by various industries under the Paris agreements are considered. The joint analysis of the operating and prospective power plants, leading industrial technologies based on CO<sub>2</sub> consumption, has revealed three types of energy-industrial symbioses representing a cost-effective "Power Plant – CO<sub>2</sub> Consumer" model. This model operates without CO<sub>2</sub> capture and conditioning unit and has the efficiency close to the traditional power plant without emissions utilization. Critical technology solutions are being developed for one of these types.

## 1. Introduction

The global decarbonization of the world energy system requires the development and implementation of new approaches to the zero-emissions power generation. Renewable energy sources can solve the problem of reducing polluting emissions to some extent. Still, for industrialized countries, a diversified generation structure is needed in which power capacity on fossil fuels is a stabilizing factor. That makes it necessary to move from a linear model to the so-called circular carbon economy by forming a neutral carbon cycle based on stable supply chains using carbon dioxide emissions as raw materials for the chemical, construction, and other industries.

The transition to low-emission operation under the Paris Agreement means that technogenic carbon released in a form convenient for consumption (depositing or utilization) will supply by heat and power generation companies as the main final product. The balanced combination of power generation and carbon utilization technologies becomes the key to ensuring the energy sector's viability on the economically acceptable level.

The problems of stricter emission standards and commitments to reduce greenhouse gas emissions require the development of environmentally and economically viable technologies to capture CO<sub>2</sub> and its subsequent utilization [1, 2]. According to global environmental programs, a scenario for reducing CO<sub>2</sub> emissions will inevitably be implemented by all industries. Still, only the power generation industry requires to switch in 2050-2060 to emission-free low-carbon technologies with a CO<sub>2</sub> emissions reduction by 80-95% compared to 1990, and other emissions by 100% [3].

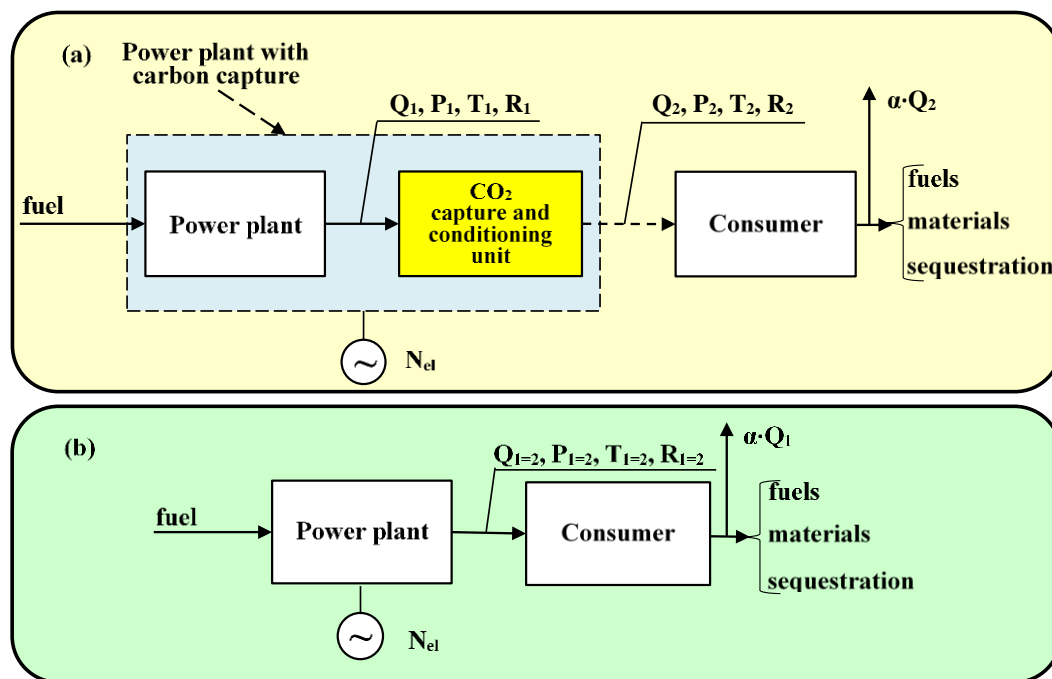


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The power generation industry and CO<sub>2</sub>-consuming industries have developed almost independently of each other, without a flows correlation of CO<sub>2</sub> from power plants and CO<sub>2</sub> used in production in terms of volume (Q), pressure (P), and purity (R).

Understanding the need for a transition to a new technological structure, the energy producer of CO<sub>2</sub> required to search for ways to radically green the work and from the consumer of CO<sub>2</sub> required the process parameters to comply with CO<sub>2</sub> parameters at power plants outlet [2, 4].

The integration of the energy complex producing heat and electricity and the CO<sub>2</sub> consumer is currently being addressed in two main directions (figure 1).



**Figure 1.** CCUS basic diagram: a) Conventional model; b) Perspective model.

The traditional roadmap on the part of the CO<sub>2</sub> "producer" is that the power generation industry is usually based on the CCS model and the idea that it is fundamentally impossible to involve all volumes of technogenic CO<sub>2</sub> in the economic turnover [1]. The model focuses on the most energy-consuming and economically unattractive carbon dioxide sequestration technologies in the ocean and geological strata. As a rule, to implement this, the carbon dioxide at the power plant outlet should be subjected to deep purification and high compression in the CO<sub>2</sub> capture and conditioning unit to harmonize the outlet CO<sub>2</sub> parameters with the "consumer" inlet CO<sub>2</sub> parameters (figure 1(a)).

Such a unit significantly increases auxiliary plant expenditures, which leads to a reduction in the net efficiency of power plants.

The roadmap from the "consumer" side considers the technogenic CO<sub>2</sub> as a raw material for production (CCU) and includes:

1. Efficiency analysis and project development for the integration of local producers and consumers of CO<sub>2</sub>.
2. The elaboration of new specialized technologies of CO<sub>2</sub> utilization, which provides the adjustment of CO<sub>2</sub> parameters at the power plant output and the consumer input.

The first issue involves the formation of territorial energy-industrial symbioses of local CO<sub>2</sub> sources and industrial consumers [4].

A special place is occupied by the development of breakthrough utilization technologies, whose technical requirements are close to the source parameters. Such techniques are focused on CO<sub>2</sub> output

parameters (concentration, pressure, and temperature) from existing power plants with the emission of large volumes of low concentrated CO<sub>2</sub> [2], to be regarded as a low-cost model of clean energy production from fossil fuels.

A consistent analysis of CO<sub>2</sub> parameters from the power plants and the potential CO<sub>2</sub> consumer's parameters is needed to estimate the power generation potential according to the perspective low-cost CCUS model without CO<sub>2</sub> capture and conditioning unit at the efficiency close to the conventional plant.

## 2. Research method

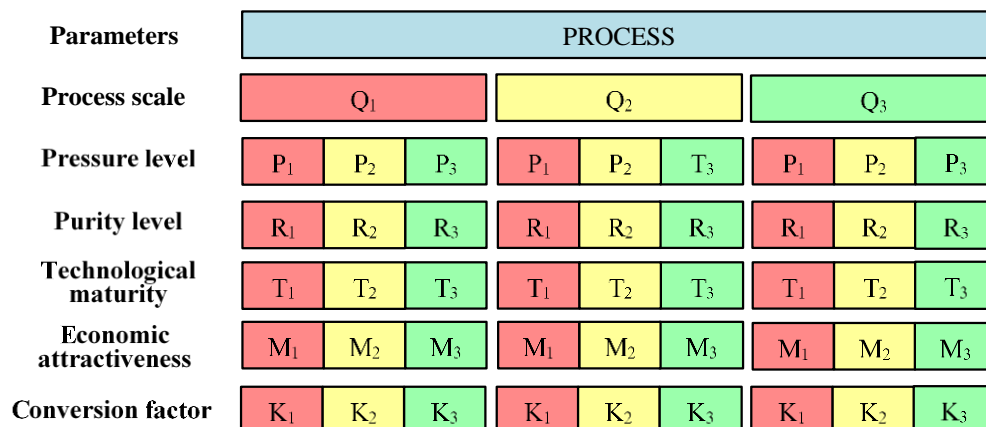
The method is based on the screening-analysis procedure of aggregated technical and economic indicators.

The coordinated parameter analysis of CO<sub>2</sub> generated by power plants and the consumers CO<sub>2</sub> potential is carried out for three main indicators most sensitive to the power generation process, namely, volume (Q), operating pressure (P), and purity (R), the level of technological maturity (T), market attractiveness (M), and conversion factor K<sub>CO<sub>2</sub></sub>. Each indicator is ranked in three levels according to its closeness to the target indicator: 1 - least successful scenario; 2 – average scenario; 3 - most successful scenario. Quantitative CCU process values for the monitored indicators are shown in Table 1.

**Table 1.** Benchmarks of CCU processes. Quantitative values.

Level	Q, MtCO <sub>2</sub> /year	P, MPa	R, %	T, years	M, thousand USD/ product ton	K <sub>CO<sub>2</sub></sub> , kg <sub>CO<sub>2</sub></sub> /kg <sub>product</sub>
1	<2.5-4	>7(8)	90-99.9	>10-15	<1	<0.5
2	5-50	0.5-7(8)	15-90	5-10	1-2	0.5-1.3
3	>50	<0.3-0.5	<15	<3-5	>2	>1.3

The algorithmic analysis scheme of the market potential for six parameters of CO<sub>2</sub> production and consumption is shown in figure 2.



**Figure 2.** Screening-analysis algorithm for CO<sub>2</sub> production and consumption technologies.

The main carbon capture technologies from the BAT catalog were chosen as the research object on the power generation side. The list was complemented by the promising developments on the Oxy-fuel IGCC.

As the research object from the consumer's side, 18 core technologies were selected from the IEA [1] list, which is characterized by the highest level of readiness for commercialization [5].

### 3. Results and discussion

#### 3.1. CO<sub>2</sub> production and consumption indicators

Power plant distribution groups according to the pressure and purity levels of the emitted CO<sub>2</sub> are shown in figure 3.

R <sub>3</sub>	<b>Power unit type I</b> <ul style="list-style-type: none"> <li>algae Q<sub>3</sub></li> <li>inorganic carbonates (ex-situ) Q<sub>3</sub></li> </ul>		
R <sub>2</sub>			
R <sub>1</sub>	<b>Power unit type II</b> <ul style="list-style-type: none"> <li>acrylates Q<sub>1</sub></li> <li>polyurethane Q<sub>2</sub></li> <li>beverage carbonation Q<sub>2</sub></li> <li>methanol Q<sub>3</sub></li> <li>methane Q<sub>3</sub></li> <li>inorganic carbonates (ex-situ) Q<sub>3</sub></li> </ul>	<b>Power unit type III</b> <ul style="list-style-type: none"> <li>polycarbonates Q<sub>1</sub></li> <li>formic acid Q<sub>1</sub></li> <li>carbarnates Q<sub>1</sub></li> <li>DME (dimethyl ether) Q<sub>2</sub></li> <li>formaldehyde Q<sub>2</sub></li> <li>ethanol Q<sub>3</sub></li> <li>inorganic carbonates (ex-situ) Q<sub>3</sub></li> </ul>	<b>Power unit type III</b> <ul style="list-style-type: none"> <li>dimethyl carbonate Q<sub>1</sub></li> <li>acetic acid Q<sub>2</sub></li> <li>industrial gas Q<sub>2</sub></li> <li>EOR/EGR Q<sub>3</sub></li> <li>urea Q<sub>3</sub></li> <li>inorganic carbonates (in-situ) Q<sub>3</sub></li> </ul>
	P <sub>3</sub>	P <sub>2</sub>	P <sub>1</sub>

**Figure 3.** Comparison of combined heat and power generation and CO<sub>2</sub> utilization technologies in terms of pressure and purity.

As Fig. 3 shows, the considered power plants can be grouped into three categories by output parameters of CO<sub>2</sub> streams in the characteristic points. These groups are generally identical to the types of CO<sub>2</sub> consumers:

I - low-pressure P<sub>3</sub>, low purity R<sub>3</sub>. Such CO<sub>2</sub> parameters are peculiar to flue gases, i.e. products of fuel combustion in the air at most power plants (PC power plants, IGCC without CCS system with Air-fuel GTU of standard parameters and NGCC);

II - low-pressure P<sub>3</sub>, high purity R<sub>1</sub>. Such output CO<sub>2</sub> parameters are typical for IGCC with pre-combustion CCS, Oxy-fuel combustion units, and IGCC with Oxy-fuel GTU of standard parameters;

III - average P<sub>2</sub> and high-pressure P<sub>1</sub>, high purity R<sub>1</sub>. Such outlet CO<sub>2</sub> parameters are obtained by new Oxy-fuel IGCC with high-pressure s-CO<sub>2</sub> GTU.

#### 3.2. Energy-industrial symbioses

Based on the data comparison shown in figure 3, three types of energy-industrial symbioses can be formed, operating on a low-cost model.

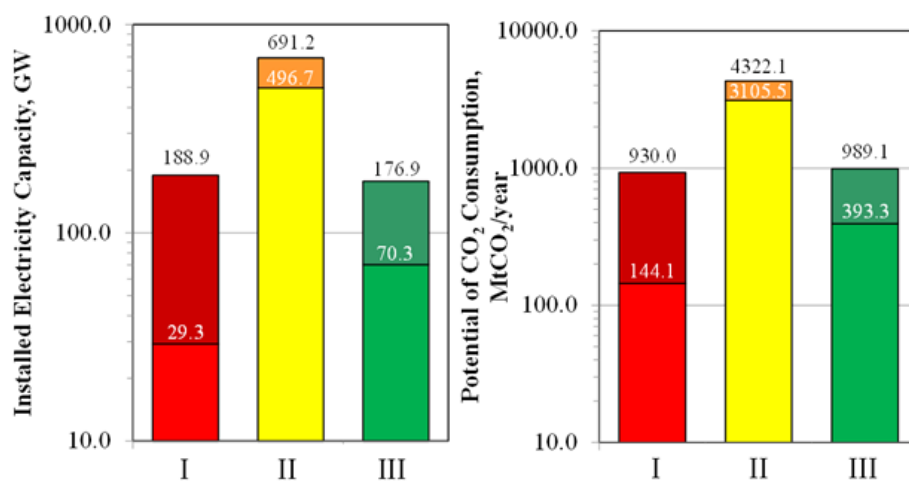
In the type I symbiosis 144.1 (930.0) Mt CO<sub>2</sub>/year can be utilized at power plants with a total net capacity of 29.3 (188.9) GW. Here and below are the minimum values in the conservative scenario and the maximum (in brackets) forecast values.

Type II symbiosis can utilize 3105.5 (4322.1) Mt of CO<sub>2</sub>/year from power plants with a total net capacity of 496.7 (691.2) GW.

In a symbiosis of type III 393.3 (989.1) Mt of CO<sub>2</sub>/year generated by the power plants with a total net capacity of 70.3 (176.9) GW, can be utilized.

The total potential of low-cost energy-industrial symbioses (LCEIS-CCU) reaches 651.4 (1116.0) GW (figure 4). This value is comparable with the installed capacity of coal-fired thermal power plants in China.

In the future hybrid energy model, such low-cost energy-industrial symbioses can take the base positions (along with nuclear and hydropower), complemented by the variability part from renewable sources.



**Figure 4.** Power generation potential in energy-industrial symbioses by type of technology.

Based on the thermal power plant with CO<sub>2</sub> emission of more than 4 MtCO<sub>2</sub>/year, it is reasonable to develop multi-tonnage utilization productions Q3, based on individual or block scheme with mono-products production. Average tonnage technologies Q2 are integrated under the group scheme with poly-products manufacturing. With low-tonnage technologies Q1, it is reasonable to supplement the Q2 and Q3 output or focus them on the mono-products production based on small cogeneration plants under the individual scheme. The latter approach was reported in [4], where for the regional local case, with a total CO<sub>2</sub> consumption of more than 0.25 MtCO<sub>2</sub>/year, synergistic effects of CCU symbioses creation had been considered.

## Conclusions

The challenge for developing an energy-industrial symbiosis generating thermal and electrical energy and marketable CO<sub>2</sub> without a noticeable efficiency loss can be solved positively if the input parameters of the CO<sub>2</sub> utilization unit match the output CO<sub>2</sub> parameters of power plant (pressure, purity, and volume).

A joint analysis was carried out for the following technologies: operating power plants from the BAT catalog updated with the latest promising developments on Oxy-fuel IGCC, as well as 18 major industrial production technologies based on CO<sub>2</sub> consumption from the IEA list. The analysis has identified three types of energy-industrial symbioses. The LCEIS-CCU works as a cost-effective model "Power Plant - CO<sub>2</sub> Consumer" without an intermediate capture and conditioning block needed for harmonization of output/input CO<sub>2</sub> parameters.

UrFU is currently developing the concept and core engineering solutions for the proposed unit, representing the symbiosis of power generation and cost-effective CO<sub>2</sub> transmission to industrial consumers "Power Generation Unit – CO<sub>2</sub>-based production". The integration with the mineralization technology will provide utilization of CO<sub>2</sub> and different wastes (ash, slag, construction industry waste) with the simultaneous production of marketable products (cement, concrete, etc.). The results of this work are presented partly in previous studies [6, 7].

## Acknowledgments

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